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Photometric Identification of Young Stripped-Core Supernovae

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ABSTRACT

We present a method designed to identify the spectral type of young (less than ~ 30 days after explosion) and nearby ($z \lesssim 0.05$) supernovae (SNe) using their broad-band colors. In particular, we show that stripped-core SNe (i.e., hydrogen deficient core-collapse events, spectroscopically defined as SNe Ib and SNe Ic, including broad-lined SN 1998bw-like events) can be clearly distinguished from other types of SNe. Using the full census of nearby SNe discovered during the year 2002, we estimate the impact that prompt multi-band photometry, obtained by 1 m class telescopes, would have on the early identification of stripped-core events. Combining this new approach with ongoing spectroscopic follow-up programs, one can expect ~ 20 nearby, stripped-core events to be identified, each year, around, or before, maximum light. Follow-up studies, including prompt, multi-epoch optical spectroscopy and spectropolarimetry, as well as radio and X-ray observations, could greatly increase our understanding of these events, and shed new light on their association with cosmological gamma-ray bursts.

Subject headings: supernovae: general

1. Introduction

Several types of supernovae (SNe) are recognized, and are most commonly determined by the attributes of the SN optical spectra. The most basic division is between hydrogen-rich (type II) SNe, and hydrogen deficient (type I) SNe (Minkowski 1941). Type I events are further divided into SNe Ia, which usually show the prominent Si II absorption trough near 6150 Å, SNe Ib, which lack this feature but show prominent He lines, and SNe Ic, whose spectra show neither (see Filippenko 1997 for a review).

Direct detection of the progenitor stars on pre-explosion images has established that type II SNe result from the explosion of massive stars, presumably following the gravitational collapse of the stellar core (SN 1987A, White & Malin 1987; SN 1993J, Aldering et al. 1994; SN 2003gd, Van Dyk, Li, & Filippenko 2003, Smartt et al. 2004). The existence of transition objects, which appear to be SNe II in spectra obtained shortly after explosion, but later evolve and become very similar to SNe Ib and SNe Ic (SNe IIb; e.g., Filippenko 1997), as well as the apparent association of SNe Ib and Ic with young stellar populations (e.g., Van Dyk, Hamuy, & Filippenko 1996), suggest that these events also result from the core collapse of massive stars. These stars are assumed to have lost most (in the case of SNe IIb) or all (in SNe Ib and Ic) of their hydrogen envelope, as well as, in the case of SN Ic progenitors, most of their helium, either through stellar winds or due to binary interaction. In contrast, SNe Ia are frequently found among old stellar populations, e.g., in elliptical galaxies, and are unlikely to be associated with very young progenitor stars. These events are commonly assumed to be the result of a thermonuclear runaway explosion of a white-dwarf star, which reaches the Chandrasekhar mass either through accretion from, or a merger with, a binary companion.

Of all the various types of SNe, the ones that are probably the least studied are SNe Ib and Ic, which will be referred to henceforth as stripped-core events. Contributing factors

probably include the intrinsic rareness, relatively low luminosity, and heterogeneity of these events, along with the absence of a high-profile science driver for such work, as provided, for example, by cosmological distance estimation for studies of SNe Ia. Most of the progress in this field was due to the (rare) occurrence of bright stripped-core events in nearby galaxies, e.g., SN 1994I in M51. The only recent comprehensive study of stripped-core events was conducted by Matheson et al. (2001).

This situation is perhaps about to change, following the emerging connection between stripped-core SNe and long-duration gamma-ray bursts, and in particular, the associations between GRB 980425 and SN 1998bw (Galama et al. 1998) and GRB 030329 and SN 2003dh (Stanek et al. 2003; Hjorth et al. 2003; Matheson et al. 2003) – see Lipkin et al. (2003) for a recent review. The amount of overlap between GRBs and stripped-core SNe is intriguing. Are all GRBs associated with a SN? Are all stripped-core SN explosions triggered by, or associated with, a GRB or GRB-like mechanism (i.e., a non-isotropic, jetted explosion; Khokhlov et al. 1999) ? Early-time studies of stripped-core SNe may provide the answer to this last quesion.

2. The Importance of Early-Time Identification of Stripped-Core SNe

A key to understanding the connection between stripped-core SNe and GRBs is whether "ordinary" SNe Ib and Ic (such as SN 1994I) and SN 1998bw-like events, associated with GRBs, are bridged by a continuum of SNe with intermediate properties. Alternatively, are there two distinct populations of SNe – those associated with GRB-like explosions, and "ordinary" stripped-core events. The existence of a continuum would support theories in which GRB-like phenomena (i.e., highly aspherical explosions) occur in all stripped-core events, with the observed variety driven by geometrical (orientation) effects, or variations in the intrinsic energy of the central GRB engine, in which case ordinary SNe are "failed

GRBs." A bi-modal distribution would suggest that the (mostly spherical) core-collapse and the (highly aspherical) GRB are two unrelated physical processes that occur simultaneously in some cases (e.g., Soderberg, Frail, & Weiringa 2004).

Since the spectral distinction between SN 1998bw-like events and normal SNe Ic becomes less pronounced with age, it is quite possible that the fact that most stripped-core events are spectroscopically observed at or after maximum brightness causes us not to detect intermediate events, which resemble SN 1998bw early on, but are already ordinary-looking when we observe them. Thus, early-time identification of stripped-core events is crucial in order to trigger spectroscopic studies of these events, as well as spectropolarimetric observations, the most sensitive tracers for explosion asphericity.

The collapsar model predicts an association between long-soft GRBs and stripped-core SNe (Woosley 1993, MacFadyen & Woosley 1999). The progenitor stars are required to have lost their extended hydrogen-rich envelopes before collapse, either to a binary companion or through mass loss by stellar winds. This is necessary for a relativistic jet to escape the surface of the star on a collapse timescale for the helium core (~ 10 s). The SNe Ic associated observationally with GRBs (SN 1998bw and SN 2003dh) are luminous, with models indicating large explosion energies ($\sim 10^{52}$ erg) and the production of large masses of radioactive Ni ($\sim 0.2 - 0.5 M_{\odot}$) (Iwamoto et al. 1998; Woosley, Eastman, & Schmidt 1999; Mazzali et al. 2003; Woosley & Heger 2003). Collapsars can produce large amounts of Ni by expelling hot material from a poorly cooled accretion disk (MacFadyen 2003) around the central accreting black hole powering the GRB. Current models incorporate asymmetry in the explosion to explain the fast rise in the light curve of SN 2003dh (Woosley & Heger 2003). Thus, early photometric observations of stripped-core SNe on the rise to maximum will better constrain the degree of asymmetry in stripped-core SNe, and, in combination with early spectra, also the explosion energy and nickel masses. These quantities are

critical to understanding the mechanism responsible for exploding the star and, sometimes, producing a GRB.

SN 1998bw was uniquely radio luminous. In spite of recent and ongoing intensive efforts (Berger et al. 2003; Soderberg et al. 2004) no similar events were discovered among ~ 60 stripped-core SNe observed so far (1999–2004). On the other hand, the late initiation of many of the radio searches may have contributed to this null result. In particular, the radio light curve of SN 1998bw peaked early, $\sim$ 5 days *prior* to optical maximum. Another SN 1998bw-like event, SN 2002ap, one of the only other detections, also peaked early in the radio band. However, with a radio luminosity 10^4 times below that of SN 1998bw, this event was only detected since it is the nearest SN in the sample (~ 7 Mpc) and was observed ≥ 10 days before optical maximum. Thus, early identification of stripped-core events would be highly valuable for radio studies of these SNe. The same is true in the case of space-based searches for the rapidly decaying X-ray emission from these events.

To conclude, early identification of stripped-core events, providing a trigger for detailed follow-up observations, would be very helpful in characterizing the little-known properties of the stripped-core SN population, as well as in searching for transition objects between GRB-associated SN 1998bw-like events and more ordinary stripped-core SNe. Such studies would further our understanding of stripped-core SN physics, and provide an important insight into the GRB-SN connection.

3. Color Classification of Young Supernovae

In Poznanski et al. (2002) we describe a method to classify SNe based on their broad-band colors. The method is based on a large number of high-quality optical SN spectra we have assembled (Table 1). This database includes observations of the

prototypical members of every well-defined SN subclass, at various ages. By redshifting the spectra and convolving them with the appropriate filter throughput curves, we derive synthetic photometry of SNe of all types at a given redshift, which can then be compared to available measurements, in order to determine, or constrain, the possible type of an observed SN. The tools we developed are quite general, and can be used to classify SNe of all the well-defined spectroscopic subclasses at arbitrary redshifts. Observations in optical bands may be used to classify SNe up to a redshift of $z = 0.75$, while infrared observation are required at higher redshifts.

In view of the growing interest in broad-lined SN 1998bw-like events, following their established association with GRBs, we have added the spectra of the two best-observed examples, SN 1998bw (Patat et al. 2001) and SN 2002ap (Gal-Yam, Ofek, & Shemmer 2002; Foley et al. 2003) to our spectroscopic database (Table 1)[1]. We then proceed to study in detail the case of nearby ($z \lesssim 0.05$) and young (less then $\sim$30 days after explosion) SNe. As we show below, young stripped-core SNe (Ib and Ic, including the SN1998bw-like events) can be clearly distinguished from all other types of SNe.

The broad-band colors of SNe are determined by their spectral energy distribution, dominated by the continuum shape. There are many spectroscopically defined subtypes of SNe. However, some of the more subtle spectroscopic divisions are erased when we examine only the continuum shape. Considering only SNe near peak brightness, we find that all subtypes of hydrogen-rich SNe (types II-P, IIn, and IIb) have similar spectra, rising steadily toward the blue all the way down to the atmospheric cutoff at $\sim$ 3000 Å. Type Ia SNe are generally bluer than SNe II at wavelengths longer than 4000 Å, beyond which a UV cutoff, attributed to line-blanketing by iron-group elements, strongly suppresses the flux (see Riess

[1]An updated version of our web-based SN-typing tool, incorporating these additional spectra, is now available at http://wise-obs.tau.ac.il/~dovip/typing

et al. 2004 for a relevant discussion). Type Ib and Ic SNe near maximum have spectra similar to each other, typically redder than both SNe Ia and SNe II, and showing a flux deficit blueward of ~ 5500 Å.

One of the peculiarities of SN 1998bw was the relatively blue spectrum observed at early times, significantly bluer than most other SNe Ic. This is demonstrated in Figure 1, showing the rest-frame spectra of SN 1998bw compared with three other nearby SNe observed close to peak brightness. Other SN 1998bw-like events, such as SN 2002ap, also have somewhat bluer continua, intermediate between those of SN 1998bw and those of "normal" SNe Ic and SNe Ib.

Inspecting Figure 1 we can see that young SNe of all types have similar continuum shapes redward of ~ 5500 Å. We are thus led to focus on bluer bands in our search for broad-band classification schemes for young SNe. Experimenting with various choices of bands, we find that $B-g$ vs. $V-R$[2] plots proves the most informative. The enhanced sensitivity one would expect to gain by analyzing also U-band data is in fact hindered by poor existing spectroscopic coverage of young SNe, resulting in sparse sampling of the relevant color spaces by our spectral database. The observational difficulties expected in performing accurate U-band photometry are likely to further impede the utility of such data. We therefore consider below mainly $B-g$ vs. $V-R$ plots.

Figure 2(a) shows the $B-g$ vs. $V-R$ color-color diagram for SNe of all types up to ~ 1 week after peak brightness. This and following figures were produced using the methods discussed in detail by Poznanski et al. (2002). A color cut at $B-g=0.24$ mag separates stripped-core SNe from other SNe (SNe Ia and SNe II). Considering only events

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[2]Throughout, we note the Johnson-Cousins and SDSS filter systems by $UBVRI$ and $ugriz$, respectively; see Poznanski et al. 2002 and references therein for exact details.

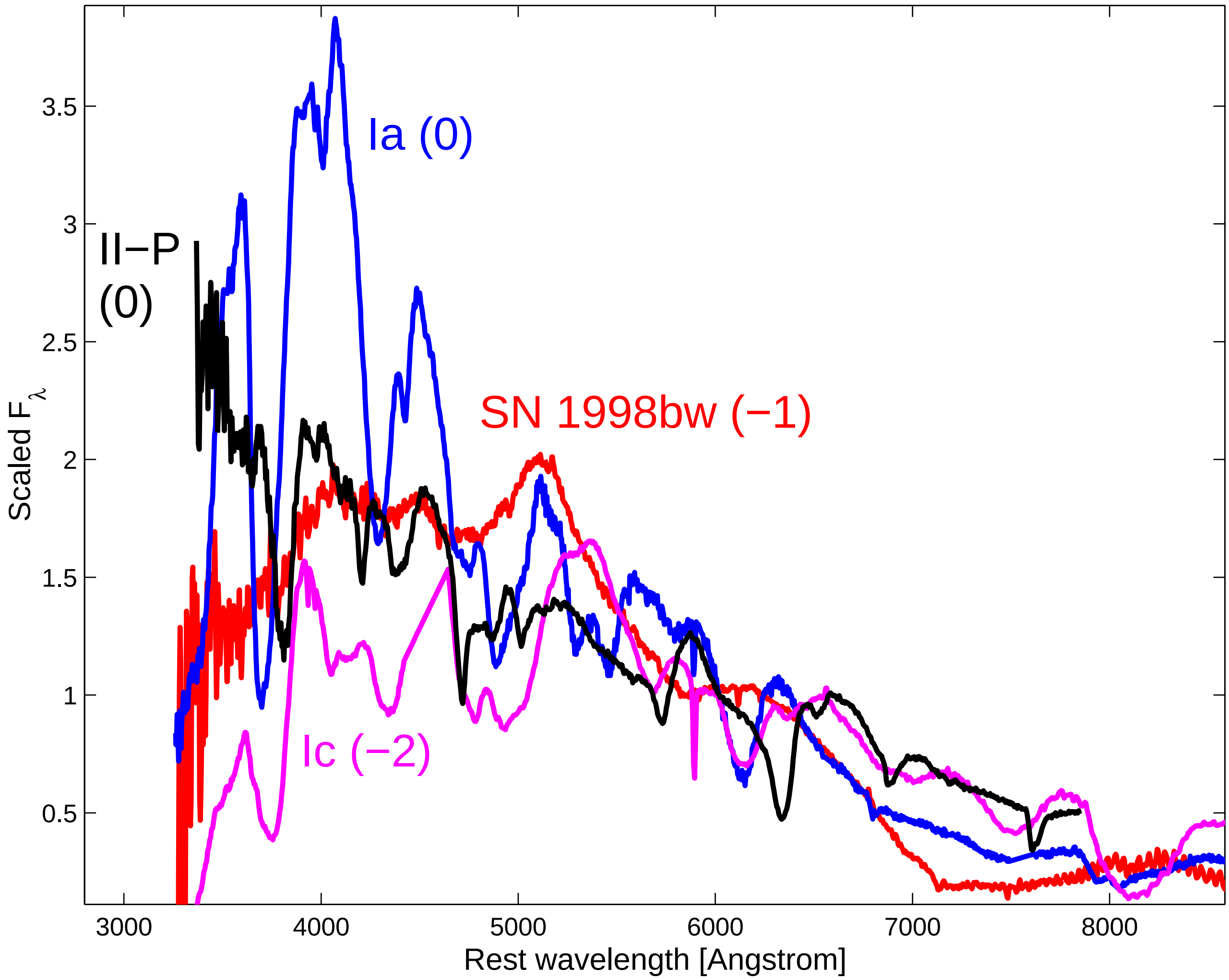

Fig. 1.— Spectra of SNe near maximum light. For clarity, we show only spectra of the prototypical SN Ia 1999ee (blue; Hamuy et al. 2002), SN Ic 1994I (Magenta; from Filippenko et al. 1995), SN II-P 1999em (black; Hamuy et al. 2001), and SN 1998bw (red; Patat et al. 2001), with ages in days with respect to B-band maximum marked. All spectra have been normalized to have the same flux around 6000 Å. Spectra of other types of SNe II (e.g., SN IIb 1993J or SN IIn 1998S) are similar to that of SN II-P 1999em, while those of SNe Ib are similar to those of the SN Ic 1994I. SN 2002ap is intermediate between SN Ic 1994I and SN 1998bw. Note how all SNe have similar spectral shape redward of 5500 Å, thus making bands redder than V less useful for classification of young SNe.

with $B - g > 0.24$ mag, stripped-core SNe form a sequence in $V - R$ colors, going from the bluest SN 1998bw, through SN 2002ap and SNe Ic, with SNe Ib being the reddest. Similar analysis can be carried out for SNe at higher redshifts. Figure 2(b) shows that for SNe at $z = 0.05$, the $g - V$ vs. $V - R$ color-color plot can be used for classification with similar efficacy.

Note that the use of these plots requires colors measured with a photometric accuracy of ~ 0.05 mag, or better. As we further discuss below, for nearby, $z \leq 0.05$ stripped-core SNe, this level of accuracy can be easily obtained with 1 m class telescopes. The plots also show the possible effects of dust reddening. For example, examining Fig. 2(a), we see that young SNe of any type are unlikely to be confused with SN 1998bw or SN 2002ap-like events, even when strongly affected by dust. Some reddened SNe II may be confused with young SNe Ib or Ic, though. Another encouraging fact is that SNe Ia, which, being the most luminous type of SNe, usually dominate flux-limited SN surveys, are unlikely to appear similar to stripped-core events, even if highly extinguished ($A_V > 1$ mag).

Classification of SNe becomes harder as they become older. Figure 2(c) shows $B - g$ vs. $V - R$ color curves computed for SNe of all types, at $z = 0$, up to ~ 2 weeks past maximum light. We can see that SN 1998bw can still be easily distinguished from all other types of SNe. While SNe Ia, between $10 - 14$ days past maximum, have similar colors to those of SN 1998bw before maximum light, elementary photometric information (i.e., if the SN is rising or declining in brightness) will differentiate between these two options. We note that highly reddened SNe Ia (with $A_V > 1$ mag), around two weeks after peak brightness, could perfectly mimic SN 1998bw, both in color and in photometric behavior. However, SNe Ia are usually detected in relatively dust-poor environments, so such events are very rare. Type II-P and IIb SNe during their second week past maximum have similar colors to SNe Ib and Ic and also to those of SN 2002ap at similar ages ($B - g \approx V - R \approx 0.4$ mag).

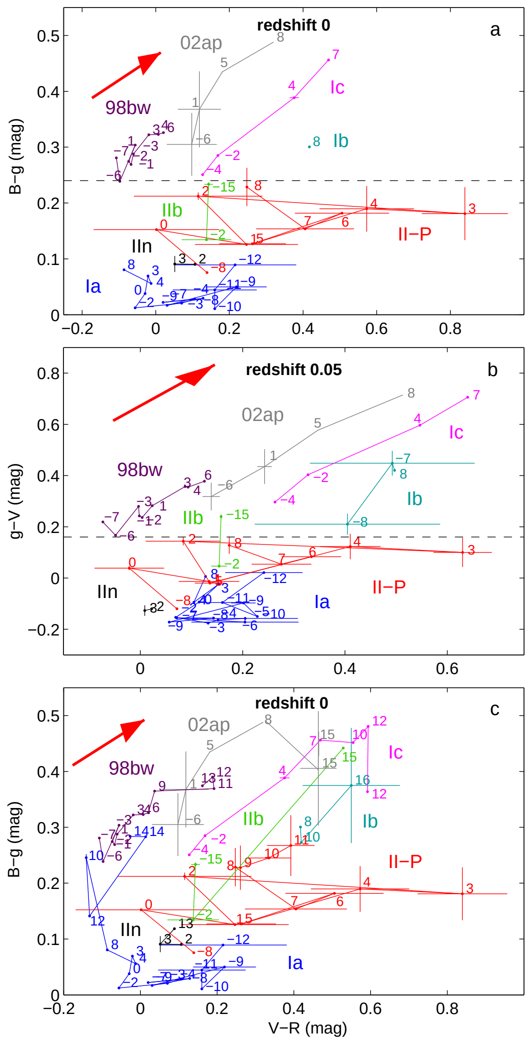

Fig. 2.— **(a)** $B-g$ vs. $V-R$ colors for SNe of all types, up to ~ 1 week past maximum light. SN ages (in days) with respect to B-band maximum light are marked. A color-cut at $B-g = 0.24$ mag separates stripped-core SNe from all other SNe. The error bars represent extrapolation uncertainties introduced when spectra do not cover the entire wavelength range of a given filter. The arrow shows the reddening effect corresponding to $A_V = 1$ mag of dust extinction. See Poznanski et al. (2002) for a full discussion. **(b)** $g-V$ vs. $V-R$ colors for SNe up to $\sim$ 1 week past maximum light, but for SNe at $z = 0.05$. A color-cut at $g-V \sim 0.16$ mag separates stripped-core SNe from most other events. **(c)** $B-g$ vs. $V-R$ colors for SNe of all types, up to $\approx$ two weeks past maximum light. Note that SNe of type II-P, IIb, Ic and Ib attain approximately the same colors ≈ 2 weeks after maximum.

Thus, these types cannot be disentangled using these colors alone.

4. Young, Nearby SNe – Current Status and Potential Improvement

In order to utilize the method described above for prompt identification of stripped-core SNe, one needs to secure accurate, multi-band photometry of each new nearby SN, as soon as possible after discovery. Stripped-core SNe of all kinds, close to peak brightness, are expected to be brighter than ~ 16 mag (~ 20 mag) at $z = 0.01$ ($z = 0.05$) in the B, g, V and R bands. Using the web exposure-time calculator for the 1.54m Danish telescope at ESO as an example, we find that a four-band photometry sequence for a 20 mag source could be obtained in less than 10 minutes (35 minutes) with S/N of 20 (50). Thus, photometry at the required level of accuracy, as specified above, could be easily obtained with a 1 m class telescope. Since less than a single suitable young SN per day is currently discovered, an early photometric classification program could be maintained at such a facility using only a small fraction of the available telescope time.

To assess the possible impact of such a prompt color-classification program, we inspect a SN sample comprised of all nearby ($z \lesssim 0.05$) SNe detected and reported in the IAU Circulars during the year 2002. We further limit our sample to SNe for which the reported photometry can be used to constrain the date of explosion. Specifically, we have compiled all those events for which the age at discovery could be constrained by pre-explosion images to be less than ~ 1 month. Considering SN rise times (i.e., the time between explosion and peak brightness, typically between one and three weeks) and the fact that most of these SNe exploded some time after the reported non-detections, we estimate that this sample is comprised mostly of SNe that are within one week from peak brightness. We have to select young SNe using an upper limit on the time since explosion, instead of their age relative to peak brightness (as done in the previous section), since the peak date is usually not

reported in the IAU Circulars, and is often unknown or poorly constrained.

In Figure 3 we plot, for the SN sample described above (blue) and for stripped-core events only (red), the distribution of delay times between SN discovery and the date of the first spectroscopic observation. As this histogram shows, spectra of only about half of the SNe are obtained promptly (within ~ 5 days). Spectroscopic observations of the rest of these "young" SNe (i.e., which were discovered at an early age) are unfortunately secured only at much later dates. Comparing the blue and red histograms, we see that the distribution of delays between SN discovery and spectroscopic follow-up for stripped-core events is the same as the distribution found for the general SN population, as can be expected in the case where no priors are used in the selection of events for spectroscopic follow-up. Similar results were found in an analysis of SNe reported in IAU circulars in the last 5 years (1998-2002) by E. Cappellaro (2004, private communication). It should be noted that the delay times shown in Fig. 3 are between the date of discovery and the date the first spectrum was obtained. In reality, further delay (of typically a few days) in the study of interesting events is caused by the time required to analyze the spectra, report them to the IAU, and for the IAU to distribute this information.

This analysis demonstrates the potential contribution of early photometric identification to the studies of SNe in general, and stripped-core SNe in particular. Of the 19 stripped-core events discovered probably within 7 days from peak magnitude during the year 2002, only 11 were identified as such within 5 days from discovery, using the combined spectroscopic resources of the entire SN-research community, which are unlikely to be significantly expanded in the coming few years. Thus, studies such as the ones described in § 2 were limited to only 58% of those stripped-core SNe which happened to be discovered early. Implementing the photometric identification procedures outlined in § 3 using a 1 m class telescope could have practically doubled the sample of objects available for this type of

research.

5. Conclusions

The emerging connection between stripped-core SNe and GRBs is likely to revitalize the study of this class of SNe. The rareness and relative faintness of these events has so far held back advancements in systematic studies of their properties, which would probably help understanding their relation to GRBs and the underlying physics. In particular, studies possible only while these SNe are young (i.e., at, or preferably before, maximum light) have been hindered by frequent delays between the discovery, spectroscopic type determination, and the announcement of the type in IAU circulars.

To facilitate prompt classification of young stripped-core SN candidates using broad-band colors, we have added the spectra of SN 1998bw, associated with GRB 980425, and the similar SN 1998bw-like SN 2002ap, to the spectroscopic data base of Poznanski et al. (2002). We have applied the methods of these authors to this expanded data base, and have studied in detail methods to classify young (around peak, or before) and nearby ($z \leq 0.05$) SNe. We have shown that stripped-core events can be efficiently selected using four-band photometry focused on the bluer bands. We have also demonstrated that the required photometric accuracy can be obtained with a 1 m class telescope, and that reddening effects do not significantly compromise our analysis. Application of this method to the SN population discovered by current SN surveys will probably double the number of young stripped-core SNe identified at or before peak magnitude, and, combined with current SN spectroscopy programs, will supply about 20 new targets each year for detailed follow-up studies in radio, optical, and X-ray bands.

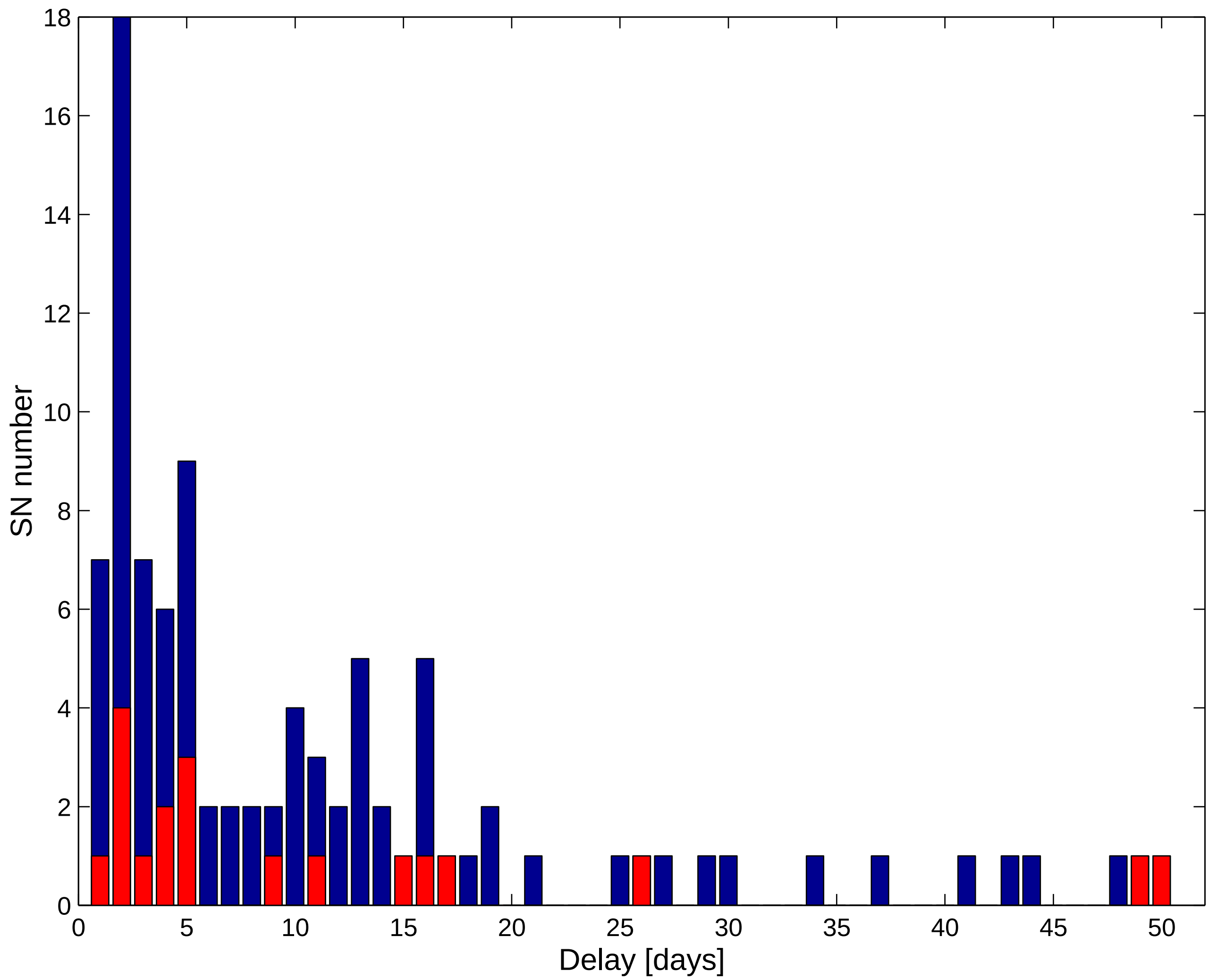

Fig. 3.— The distribution of delay times (in days) between the SN discovery and the date of the first spectroscopic observation, for all "young" SNe (see text) discovered during 2002 (blue) and for the subset of stripped-core SNe (red).

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Table 1. SN Spectral Database

Type	SNe	Epochs	Redshift	References[a]
Ia	1994D	22	0.0015	1,2
	1987L	2	0.0074	1
	1995D	4	0.0066	2
	1999dk	5	0.0150	2
	1999ee	12	0.0114	3
Ib	1984L	12	0.0051	1,2
	1991ar	1	0.0152	4
	1998dt	2	0.0150	4
	1999di	1	0.0164	4
	1999dn	3	0.0093	4
Ic	1994I	14	0.0015	1,5
	1990U	8	0.0079	4
	1990B	4	0.0075	4
II-P	1999em	27	0.0024	6
	1992H	13	0.0060	1,2
	2001X	12	0.0049	2,7
IIn	1998S	13	0.0030	8,9
	1994Y	1	0.0080	1
	1994ak	1	0.0085	1
IIb	1993J	12	0	1
	1996cb	3	0.0024	10
Ic (98bw-like)	1998bw	25	0.0085	11
	2002ap	19	0.0022	12,13
Total		216		

Note. — Data from Poznanski et al. (2002) listed in the upper part of the table. Spectra of SN 1998bw and SN 2002ap added in work study are listed below. No extinction corrections were applied. SNe studied by Poznanski et al. (2002) were selected to avoid highly extinguished events. Low extinction values are also reported for SN 1998bw ($A_V \leq 0.2$; Patat et al. 2001) and for SN 2002ap ($A_V \leq 0.1$; Takada-Hidai, Aoki, & Zhao, 2002).

[a](1) Filippenko 1997; (2) Unpublished spectra by Filippenko and collaborators, obtained and reduced as those presented in (1), (4)–(6) and (8); (3) Hamuy et al. 2002; (4) Matheson et al. 2001; (5) Filippenko et al. 1995b; (6) Leonard et al. 2002; (7) Gal-Yam

& Shemmer 2001; (8) Leonard et al. 2000; (9) Fassia et al. 2001; (10) Qiu et al. 1999; (11) Patat et al. 2001; (12) Gal-Yam, Ofek, & Shemmer 2002; (13) Foley et al. 2003.